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It has recently been demonstrated that femtosecond-laser generated proton beams may be focused[1]. These protons, following expansion of the Debye sheath[2], emit off the inner concave surface of hemispherical shell targets irradiated at their outer convex pole. The sheath normal expansion produces a rapidly converging proton beam. Such focused proton beams provide a new and powerful means to achieve isochoric heating to high temperatures. They are potentially important for measuring the equation of state of materials at high energy density and may provide an alternative route to fast ignition[3]. We present the first results of proton focusing and heating experiments performed at the Petawatt power level at the Gekko XII Laser Facility at ILE Osaka Japan. Solid density Aluminum slabs are placed in the proton focal region at various lengths. The degree of proton focusing is measured via XUV imaging of Planckian emission of the heated zone. Simultaneous with the XUV measurement a streaked optical imaging technique, HISAK, gave temporal optical emission images of the focal region. Results indicate excellent coupling between the laser-proton conversion and subsequent heating.

I. Introduction

Fast Ignition fusion is an attractive means to eventually achieve high fusion yields with potentially more modest methods[4]. Extensive studies of relativistic electrons from short-pulse high intensity lasers have shown that the coupling of laser energy into hot electrons can be very efficient[5], encouraging to the fast ignition concept. The characteristics of these hot electrons have shown occasionally stochastic behavior. Indeed in the presence of modest scale-length pre-plasma deflection and spraying of the relativistic electron current has been consistently measured[6,7]. These initial experiments on the LLNL Nova Petawatt Laser System also showed extremely intense and energetic proton beams [Ref 2] emitted normal to rear target surfaces with emission regions many times larger than the laser focal spot. The advantageous energy deposition characteristics of ions and the excellent energy efficiency into protons quickly lead to the concept of proton fast ignition. Ref[1]

The energy density available from dE/dx stopping from protons versus electron is higher given MeV range particle energies. More importantly is the desirable trait that TSNA driven protons have fairly predictable trajectories. It is this combination of high energy density and predictable proton beam directionality that we may now exploit in creating hot matter in a time short compared to its expansion time. Initial experiments in proton focusing have been recently performed at LLNL on the JANSP Laser System. Optical pulses of 100 fs Ti:Saphire light at 10 J were focused onto hemispheres and the resultant proton beam was directed to a foil. Optical emission in the visible from Planckian heating diagnosed the focused protons.

We now extend this work into the longer pulse and higher energy Petawatt regime. The Gekko Petawatt Laser System at ILE – Osaka University is used for in this study. It has available over 200 J of optical energy in .8 picoseconds enabling vastly higher energy densities at a target surface.

II. XUV Imaging Diagnostic for Proton Heating Experiment.

Proton heating of solid density matter as performed here happens on time scales comparable to that of the laser. Estimations of proton acceleration times are in the few to tens of picoseconds. Stopping of protons in thin layers of material happens on similar time scales. As matter heats above a few eV in temperature, light emission in shorter wavelengths becomes measurable following Planck's law. We have designed an XUV band imaging microscope operating at 68 eV with an optical band pass of 8 eV, constructed of Mo:C:Si multilayer mirrors on super polished substrates. The focal length of the imaging optic is 308 mm and we combine this with a 45-degree turning mirror for noise reduction into an imaging device of magnification of 13x. A Princeton Instruments cooled CCD camera with and ST 138 controller is used to acquire the XUV image at the image plane. The CCD is a SITE back-thinned back illuminated 1Kx1K format poly silicon chip optically filtered to dark with a 1000 angstrom Aluminum filter. The mirror peak reflectivity is just below the Aluminum L-edge at 71 eV. There is considerable debris in ultra-high intensity laser experiments. A spinning mirror holder beneath a fixed aperture allows for an undamaged mirror surface to be rotated into place between shots. Auxiliary shielding is strategically place to reduce both stray light and hard x-ray noise.

III. Proton Focusing Following Target Sheath Normal Acceleration

Conversion efficiencies of laser-proton acceleration has been measured for laser intensities of 10^{19} $_{\text{to}}$ to 10^{20} W/cm^2 in the range of 1-10%. A simple model for proton beam divergence and beam emission diameters provides an estimate for surface curving to approximate proton focusing conditions for a particular energy of proton. We are interested in high temperature heating. Our prior observations of proton spectra having

Boltzmann characteristics (higher energy in the center of the beam lower in the outer reaches) allow us to design effective hemi-spherical shell radii to concentrate proton flux at a particular depth from the shell apex. We may test this hypothesis with translation of the target foil with in the model proton beam "waist". Fig 1.

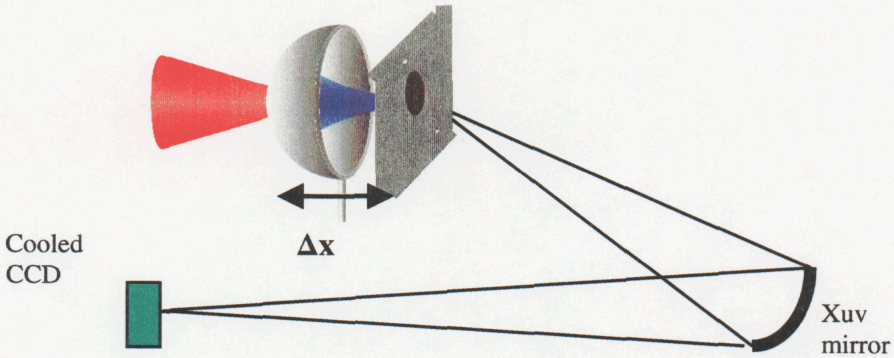
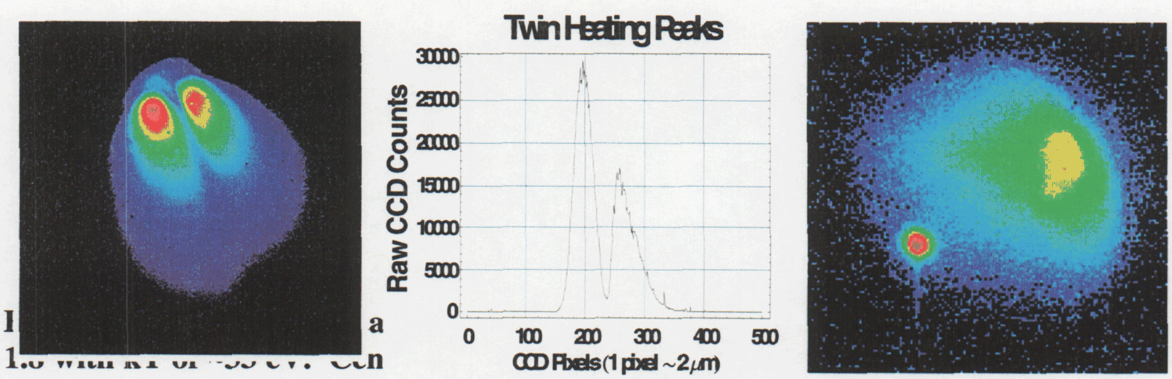


Figure 1. Nominal XUV proton heating and imaging setup. 68 eV microscope images rear surface of heated Aluminum foil. Translation of foil through various positions with regard to hemi-spherical shell radius gives different proton irradiance. Foil thickness directly relates to proton energy. eg. 100 μm Al corresponds to 3.5 MeV protons. In a sense, XUV imaging the rear target surface primarily samples heating from those protons, which stop within an optical depth of the surface or .2 μm in Al.

Initial experiments were performed with Aluminum shell diameters of 360 μm and proton target Al foils of 100 μm thick. We characterize the proton focus with the ratio of d/r, where d is the distance from shell apex to rear target surface and r is the radius of the shell. Shells are nominally 15 μm thick. General Atomics supplied all targets and are ready to build more. The d/r range for these experiments is from 1.2 to 2.5 where we initially anticipated the d/r ratio of 1.2 to be near best focus. The Gekko Petawatt Laser is focused to the apex of the Aluminum shell apex. It has a spot size of 40 x 60 μm as measured with an x-ray pinhole camera. This provides a few 10^{19} W/cm^2 in laser intensity and we estimate approximately 40% of the average 170 J of laser light is converted into hot electrons.



evident. Main peak is narrow with fwhm of 72 μm. Right, x-ray pinhole camera image of same shot from front (shell) direction. Large diffuse spot is Petawatt Laser focal spot region and attendant hot electron induced heating of surface of shell. Small intense (saturated!) spot is 20 μm diameter emission of Kilo-Volt x-rays located near the center of the proton beam entrance into the target foil.

Three outstanding results are found in this experiment. First is the demonstration of high heating to and estimated temperature of kT of ~66 eV. Second is the verification of proton heating as opposed to electron heating. This is evidenced in simultaneous XUV and x-ray K-alpha imaging of Cu 8 keV emission in a Cu doped 60 μm Al target. The strong xuv image has in this case a fwhm of 80 μm while the very weak electron impact ionization induced Cu k-alpha image has a fwhm of 363 μm. Third is the demonstration that proton induced heating is more efficient than direct laser-electron induced heating. We shot a 100 μm Al target with a 1 μm CH front layer to measure the direct heating at the rear surface of electron induced heating. A narrow heated region is evident with a fwhm of 52 μm and a peak temperature of 16 eV. This compares to the lowest heating induced by protons measured here at the d/r ratio of 2.5. This is the most out of focus condition for this experiment. Evidently electrons more effectively couple to accelerating protons than in heating parent material. The protons born as such are then very effective at accurately transferring this energy to a target material. Figure 3 summarizes the target translation experiment.

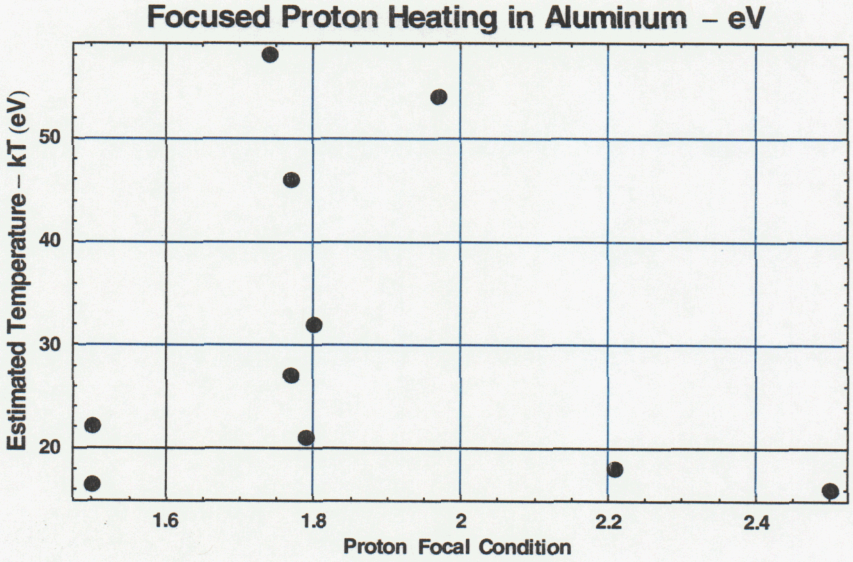


Figure 3. Summary of target foil translation to estimate best focus of proton beam. From this data, though scattered, evidence is that we go through best focus at a d/r ratio of 1.8 – 1.9. High enforced heating is also seen for these focal conditions of above 50 eV. Comparison to direct laser-solid heating (~ 16 eV) is favorable at 3 to 4 times better.

IV. Energy Characteristics of Focused Protons and Higher Heating

Our present models for TNSA driven proton spectra have Boltzmann like temperatures on the order of the ponderomotive potential, $U_p = - mc^2(\gamma-1)$ and for the conditions of the present focal spot size U_p is ~ 1-2 MeV. Considering that the surface of last stopping (we have approximated cold stopping powers here) contributes the majority of heating induce XUV emission, thinning the rear surface should expose those protons from the higher number-density, lower energy part of a Boltzmann distribution. We chose the d/r ratio of 1.5 for this experiment and varied 4 thickness' of the target Aluminum from 100 μm and the 60, 47 and 15 μm respectively. The five system shots for this condition are summarized in Figure 4. There is and overall trend in the increase in heating. The high of 66 eV is the hottest measurement of proton heating yet made.

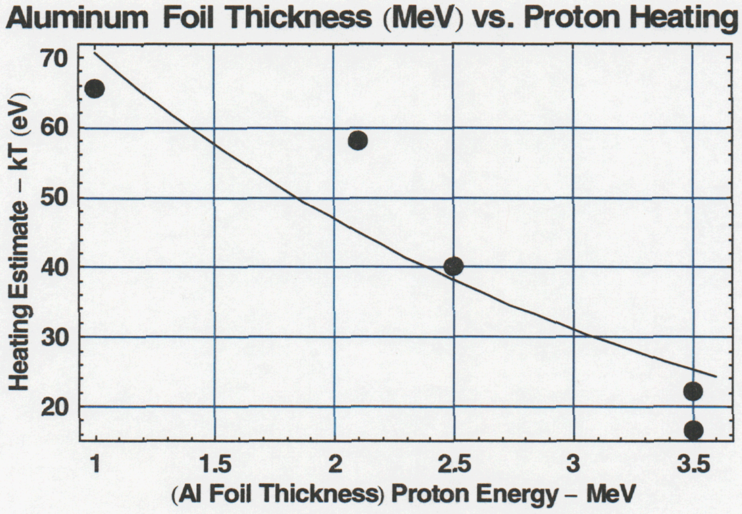


Figure 4. Summary of Aluminum foil thickness variation on observed heating. For thickness (proton energy) of 100 μm (3.5 MeV), 60 μm (2.5 MeV), 47 μm (2.1 MeV) and 15 μm (1 MeV) there is an overall trend in increased heating. Also shown is curve of a 2.5 MeV proton Boltzmann distribution. Though XUV emission from heating is proportional to proton flux it could be strongly non-linear for < 40 eV temperatures. Above this temperature, the relationship between energy deposited and XUV emission tends to linear.

V. Summary

We present preliminary data supporting the demonstration for the first time of high-temperature enforced heating in solid density matter by laser driven proton beams with estimated temperatures as high as 66 eV. This TSNA method of proton acceleration and subsequent target heating is 2-4 times more efficient than by direct laser heating (electron-ion) of laser-solids alone. The results indicate proton focusing at a d/r ratio of 1.8-1.9. Highest heating is associated with the lower-energy part of the proton spectrum. The electron content in the observed heating is found to be a minority component. Observed kilo-Volt x-ray emission from the front surface of the proton target foil indicate new and interesting physics remain researched.

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